Strategic Technology Development for Future Mars Missions

Mars Science 2013-2023

Note: This document is a draft that is being made available for comment by the Mars exploration community. Comments should be sent by Aug. 7, 2009 by e-mail to Jack Mustard, and Samad Hayati (John_Mustard@brown.edu, samad.hayati@jpl.nasa.gov)

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1 Executive Summary

A number of missions have been identified as candidates for future Mars exploration. These missions, their science rationale, and their characteristics have been fully described in a series MEPAG position white papers developed for the decadal survey. This white paper focuses on identifying *enabling* technologies for these missions. This white paper provides a description of these technologies, their current status, and their cost and schedule estimates.

Candidate missions considered are: 2016 Trace Gas Orbiter, 2018-2020 Mid-Range Rover (MRR), 2018-2020 Net Lander, and 2020+ Mars Sample Return (MSR) missions. Below we provide a summary of technologies that would be needed for these missions.

2016 Trace Gas Orbiter (TGO): The 2016 TGO mission concept would not require any new enabling technology.

2018-2020 Mid Range Rover (MRR): The MRR mission concept (a sample caching and in-situ rover mission) would require the following enabling technologies: Entry, descent, and landing (EDL) (precision landing and hazard avoidance); forward planetary protection (round-trip viable organism contamination avoidance); rock core sample acquisition, handling, and encapsulation; and rover technology (advanced autonomy to enable 20 core sample acquisition and distributed motor control to reduce complex cabling, simplify design, fabrication and testing).

2018-2010 Network Lander: This candidate mission would not require any new technology if it were based on soft landers such as the Phoenix lander. If the architecture of the mission were based on rough landers, a host of technologies would be required to ruggedize the science instruments and the subsystems, i.e., batteries, avionics, solar panels, and a capability to deploy the science instruments.

2020+ Mars Sample Return (MSR) mission: Assuming that there is a cache on the surface of Mars obtained by the proposed MRR mission, a number of technologies would be required to return the cache to Earth. As currently conceived, this mission would have two components: MSR lander and MSR orbiter. The lander enabling technologies would be EDL (precision landing improvements relative to the MRR lander); Mars Ascent Vehicle (MAV); and lightweight, low-power avionics for a lightweight fetch rover. The MSR orbiter would require the following enabling technologies: Rendezvous and sample capture to track and rendezvous with the Orbiting Sample (OS) and capture it; back planetary protection technology to avoid the possibility of contaminating the Earth with Mars organisms; and Earth Entry Vehicle (EEV) to deliver the Martian samples to Earth safely while maintaining containment.

Enabling technologies would also be required to protect and contain the samples in a Sample Receiving Facility (SRF), referred to as Mars Returned Sample Handling (MRSH) technologies.

Technologies identified and discussed in this document are those that would enable missions identified above and which could be developed in the 2011-2020 timeframe. Capability enhancements that would not be required to enable the above candidate missions are not addressed.

2 Introduction

A number of missions have been identified as candidates for future Mars exploration. These missions, their science rationale, and their characteristics have been described in a series MEPAG position white papers developed for the decadal survey. As such, this white paper does not discuss the science or the mission architectures of these candidate missions. The intent of this white paper is to provide brief and concise information regarding technologies together with the associated cost and schedule for the candidate missions.

The candidate missions that have been identified are:

- 2016 Trace Gas Orbiter Mission
- 2018 or 2020 Mid-Range Rover Mission
- 2018-2020 Net Lander Mission
- 2022+ Mars Sample Return Mission

To reduce cost and risk, these candidate missions would build upon capabilities and the experience gained during a decade and a half of sustained effort to investigate Mars remotely and *in-situ*. Many new capabilities such as entry, descent, and landing; complex *in-situ* and remote science instruments; high bandwidth direct and relay communication; mobility and autonomy; as well as continuous ground operations with fast command turnaround capabilities would be required to develop these future Mars missions.

Technologies identified and discussed in this document are those that would enable missions identified above and that could be developed in the 2011-2020 timeframe. Capability enhancements that would not be required to enable the above missions are not addressed. Below we provide high-level information regarding these candidate missions and their technology needs. These technologies and their development are elaborated in sections 3 through 11. Section 12 provides cost and schedule estimates to mature these technologies to Technology Readiness Level (TRL) 6 [2]. This TRL maturity is essential to reduce the mission risk and therefore cost and should be reached by the Preliminary Design Review (PDR).

2016 Trace Gas Orbiter Mission:

This candidate mission would not require new technologies. Capabilities developed for prior orbiter missions, i.e., Odyssey and Mars Reconnaissance Orbiter (MRO), would be sufficient to develop this mission. Needed science instruments would require enhancing technologies rather than enabling. Details are provided in the Science Instruments Section (Sec. 11) in this document.

2018 or 2020 Mid-Range Rover (MRR) Mission:

This candidate mission would have two related, but distinct, objectives. One objective would be to screen, select, core, encapsulate, and develop a cache to be returned by a future MSR mission. The second objective would be to perform *in-situ* investigations beyond what would be needed to identify samples for caching purposes.

The first objective would require new sampling and sample handling technologies to be developed. In order for samples to satisfy sample-return science and planetary protection (PP) requirements, the samples would be constrained to a maximum level of contamination by viable organisms and organic materials. From the planetary protection point of view, there would be a requirement for limiting the probability of viable Earth organisms in the cache. This is referred to as Round-Trip PP in this document.

In addition, to satisfy proposed MSR requirements on the samples collected, assuming at least 20 core samples within one Earth year of operations on the surface of Mars [1], new capabilities must be developed. Precision landing and hazard avoidance to land near the targets of interest such as outcrops would be needed. In order to increase the rover's traverse speed and at the same time satisfy stringent safety concerns, new capabilities in rover autonomy and computational capability would be needed.

New science instruments required for the *in-situ* investigation portion of such a mission are described in Section 11.

In summary the following technologies would be required:

- Sample Acquisition and Handling (Section 7)
- Round-Trip PP (Section 6.1)
- Precision Landing and Hazard Avoidance (Section 4)
- Rover Technology (Section 10)
- Science Instruments (Section 11)

2018-2020 Network Lander Mission:

A network lander mission would not require any new technology, if it were based on soft landers such as the Phoenix type lander. If the architecture of the mission were based on rough landers, i.e., a minimalist lander without a propulsion system to slow the lander, a host of technologies would be required to ruggedize the science instruments and the subsystems, i.e., batteries, avionics, solar panels, and science instrument deployment capability. An estimate for rough lander technologies is provided in Section 12.

2020+ Mars Sample Return Mission:

The proposed MSR mission has been studied in some detail in the last 10 years. Two candidate MSR mission architectures are discussed here: a) two-launch and b) three-launch architectures.

The two-launch MSR architecture concept would consist of a sampling rover to obtain a cache, and a MAV to place the samples into a Mars orbit. Both the rover and the MAV would be launched with the MSR lander. A separate MSR orbiter would then capture the sample canister called Orbiting Sample (OS) and return it to Earth.

The three-launch MSR architecture concept would consist of a sampling rover that would be launched with the first lander. This rover would screen, acquire, and seal a cache for a second lander to pick up. The second lander would land a MAV and a small, "fetch" rover near (~6 km) the cache left by the previous lander. The fetch rover would rendezvous with the cache and transport it to the MAV. The MAV would then place the OS in a Mars orbit, where the separate MSR orbiter would capture the OS and return it to Earth.

Technologies identified for the 2018-2020 MRR mission described above satisfy a portion of the proposed MSR mission technology requirements. The remaining technologies that are enabling for MSR are:

- MAV (Section 8)
- EEV (Section 5)
- Back Planetary Protection (Back PP) (Section 6.2)
- Mars Returned Sample Handling (MRSH) (Section 6.3)
- Rendezvous and Sample Capture (Section 9)
- Rover Technology (Section 10)

3 Historical Background and Cost Estimates

During the 1999 MSR mission pre-project phase, enabling technologies for MSR were identified and some progress was made in advancing those technologies. In 2004, NASA restarted the technology program for a proposed MSR mission to be launched in 2013. The Mars Technology Program (MTP) developed detailed task plans for developing all enabling technologies and funded the development of these technologies. This technology development was halted after about six months. Next, NASA organized a MSR Technology Workshop in February of 2008. This workshop updated the technology development plans based on up-to-date information of state-of-the-art. Participants were from NASA centers, universities, and industry and included those individuals that were familiar with the MSR mission concept and its required technologies.

The material described in this white paper has been written by a number of individuals who have worked on the MSR technology development plans in the past. The cost estimates are based on the historical cost estimates developed in 1999, updated in 2004, updated further in 2008 at the MSR Technology Workshop. These figures were further updated based on the MSL experience and with added reserves depending on the risk level of the specific technology. Cost numbers presented are in FY'2009 dollars.

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[2] Mankins, John C. "TECHNOLOGY READINESS LEVELS, a White Paper." http://www.hq.nasa.gov/office/codeq/trl/trl.pdf

4 Entry, Descent, and Landing (EDL)

NASA has invested substantial funds in developing EDL capabilities since 1970s. Current capabilities provide airbag landing for landers that weigh ~200kg and propulsive capabilities for more massive landers. The Mars Science Laboratory (MSL) planned to launch in 2011 will demonstrate several EDL technology advances that include: hypersonic entry guidance to improve landing precision to ~10 km from the target; Phenolic Impregnated Carbon Ablator (PICA) tile Thermal Protection System (TPS); increase in parachute diameter to 21.5 m; aeroshell diameter of 4.5 m (larger than Apollo); Mars Lander Engines (MLE); and the "skycrane" configuration in which the rover is lowered slowly to the surface on its wheels with no landed platform [1]. The mass of the landed asset (Curiosity rover in this case) is ~925 kg which can be landed at zero MOLA (elevation with respect to the Mars Orbiter Laser Altimeter (MOLA) reference ellipsoid). Robotic missions in the near future would likely use the MSL EDL system design as a baseline.

The future robotic missions would require an increase in landing precision to ~5-7 km from the target, hazard avoidance when targets of interest are near hazardous terrain, and the capability to deliver a landed mass that might exceed MSL's by up to ~10%. Limiting the increase in landed mass to ~10% over MSL might avoid the significant expense associated with a step up in launch vehicle capability to the Delta IV Heavy class. Technologies associated with these requirements are identified below.

Precision landing: Landing within ~5-7 km of the target might be achieved by several techniques. Based on recent studies, the most promising results—those that achieve this performance without large increase in the system complexity—would be obtained by reducing - entry attitude initialization error prior to entry and using a range trigger for deployment of the parachute. Detailed simulations have demonstrated that these modifications necessitate only a minor extension to MSL's entry guidance algorithm [2]. Ramifications of adopting a range trigger on site elevation must be fully understood in order to satisfy both the requirement for increased precision and the requirement for increased landed mass to zero MOLA.

Landing precision might be improved further, to ~100 m [3, 4], using terrain-relative navigation with sensors such as those currently planned to be developed by NASA's Autonomous Landing and Hazard Avoidance Technology (ALHAT) [5, 6] and improvements in guidance algorithms in entry and powered descent to minimize the additional expenditure of propellant required to fly to the target. However, this increased landing precision would impose a requirement to be able to divert to the target, which would require additional propellant in amounts that might exceed system capacity. This same technique could also be used to execute divert maneuvers to avoid hazards for landing with modest amount of additional propellant.

Increased landed mass. The MSR lander would be architected to use the MSL EDL architecture with minimal modifications. Historical trends, however, show that there could be a mass growth that is not anticipated at this time. The following technology description may indicate that minor mass growth (~10%) may be addressed without a major modification of the MSL EDL architecture. Technology options to deliver increased mass to zero MOLA would be:

- Increased entry vehicle angle of attack which increases Lift-to-Drag ratio (L/D)
- An increase in the diameter or deployment Mach of single supersonic chute; two-chute systems, (with the second chute deployed after the first, at a lower Mach number). These were considered early in the design history of MSL and are currently under investigation in the NASA multi-center EDL Systems Analysis study. Partially successful high-altitude deployment flight tests of a subsonic chute were performed in 2003-04.
- Various modifications to the MSL descent stage (lightweight, increased fuel capacity, modified propulsion system) to be considered as alternatives.

Aerodynamic investigations including wind tunnel testing of an MSL configuration have shown that the MSL EDL system should accommodate an increase in L/D to 0.4 (from MSL's 0.24) with no new technology development; however, additional analysis is recommended to validate this estimate. The parachute system enhancements would require high-fidelity simulation, ground testing, and possibly flight testing.

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5 Earth Entry Vehicle

An extremely highly reliable EEV that would return Mars samples to our planet's surface would be required, as part of meeting the Back Planetary Protection requirements (see section 6.2). The EEV would travel to Mars connected to the Orbiter/Earth Return Vehicle (ERV), wait for insertion of the OS, travel back to Earth as part of the ERV, and then would be targeted for Earth impact and released. The EEV would provide the thermal and acceleration environments necessary to maintain containment and preserve the samples for maximum scientific value.

Detailed studies have shown [1-5] that in order to meet the stringent containment requirements of the mission, the EEV should possess particular design attributes. First, the vehicle must be "self-righting," so that it would quickly stabilize itself in a heatshield-forward orientation should the release from the ERV, a micrometeoroid impact, or some other anomaly cause it to enter the atmosphere in any other orientation. Second, the EEV would have no parachute or other deployable drag device, since the reliability of such a device is much less than required. (In order to meet the reliability requirements imposed by the Back PP, the capsule would have to be designed to take an Earth impact load anyway, in the event of a failure of the drag device.)

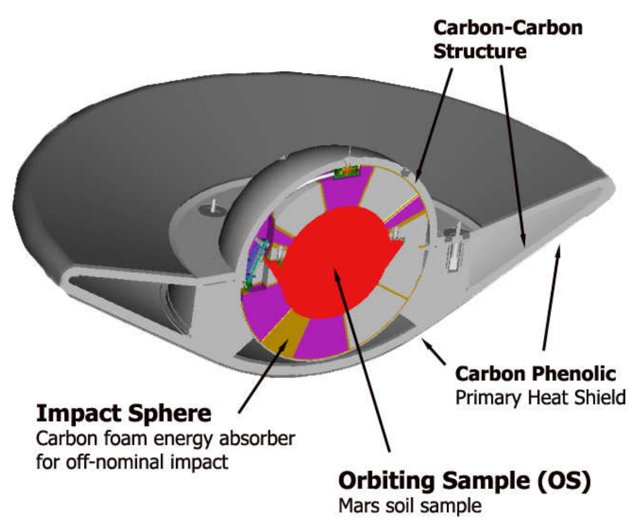

Figure 1. NASA's Current EEV Design

In the 2000 timeframe, NASA developed a detailed conceptual design of the MSR EEV. This design was supported by wind tunnel and impact testing, and is shown in Figure 1. The main features were a Carbon-Carbon structure, carbon foam impact absorption, a particular aftbody shape shown to be self-righting, and a carbon phenolic heatshield. The basic design is still valid today, but would need to be revisited for any updated mission requirements such as sample mass, OS size, contamination mitigation strategy, temperature, and impact load. The design would also benefit from materials and process improvements developed over the last 10 years. All of the component technologies are available today, with the exception of the carbon phenolic heatshield material. Our country has almost no supply of the heritage rayon used to make the historical carbon phenolic, which has flown thousands of times in military applications and which forms the basis for the high reliability heatshield required for MSR. Rayon processes have changed, and the carbon phenolic made from this new rayon would have to be proven equivalent to the heritage material. New heatshield materials available today might be considered for their micrometeoroid tolerance. In addition to these updates, the current EEV design would require rigorous ground testing to ensure the reliability and the construction of an Engineering Development Unit to validate the systems engineering.

Detailed development schedules and costs have been developed for the EEV. Within the development path, there are no low-TRL components or extreme risk items; the biggest challenge would be to adequately prove the reliability of the components and the system. The current technology plan does not include a dedicated flight test, which many experts agree is needed to validate the one in a million system reliability, since the entry flight environment cannot be replicated in ground-based facilities. The flight test would be performed by the project, shortly after the mission PDR.

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[2] Mattingly, R; Hayati, S; and Udomkesmalee, G.; "Technology Development Plans for the Mars Sample Return Mission", IEEE AC paper #1518, January 2005.

[3] Dillman, R.; Laub, B.; Kellas, S; and Schoenenberger, M.; "Development and Test Plans for the MSR EEV", 2nd International Planetary Probe Workshop, August 2004.

[4] Gershman, R.; Adams, M.; Mattingly, R.; Rohatgi, N.; Corliss, J.; Dillman, R.; Fragola, J.; Minarick, J.; "Planetary Protection for Mars Sample Return", COSPAR PTP1-0011-02, 2002.

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6 Planetary Protection

The search for life in the solar system, using either *in situ* analysis or sample return, brings with it special technical challenges in the area of planetary protection. Planetary protection requires us to preserve biological and organic conditions for future exploration and to protect the Earth from potentially harmful extraterrestrial life as a result of sample return [1]. This is essential to avoid contamination that would obscure our ability to find life elsewhere if it exists and to ensure that we take prudent precautions to protect Earth's biosphere in case it does [2]. The first Decadal Survey [3] recognized the importance of planetary protection to many classes of planetary missions and voiced the need for investment in enabling technologies. Since the first Decadal Survey, fundamental planetary protection requirements have not changed, and there have been advances in relevant aspects of our technology planning and development. In spite of these advances, there is still a need for significant investment and further progress in planetary protection technologies to enable compliance with current and prospective new requirements.

All previous missions to Mars have responded to planetary protection requirements by limiting contamination of Mars with Earth organisms based on the policies in place at the time, including the very successful Viking Mission of 1976, which conducted a system-level sterilization of the entire landed system. A future MSR mission (or series of interconnected missions) would be called upon to deal for the first time with two additional types of planetary protection requirements. The first requires protection of the Earth's biosphere from potential biological hazards in the returned samples. The second arises from the need to keep the returned sample free of "round-trip" Earth organisms in order to avoid their interference with biohazard and life detection testing of martian samples upon return to Earth. In addition, it is significant to note that any MSR precursor mission planning to acquire and cache samples for subsequent return to Earth would have to be able to satisfy the requirement to avoid Earth-sourced biological contamination of the samples. This "round-trip" requirement is not new; it traces to the COSPAR and NASA planetary protection policies and explains why MSR missions would have to meet the same forward planetary protection requirements as a life detection mission, regardless of the location on Mars explored or what *in situ* science is conducted. Technologies needed to address the protection of Earth are described in the "back planetary protection" section below, and the implementation options with their associated biological cleanliness challenges are described under "forward planetary protection."

The NASA Planetary Protection Officer (PPO) has provided draft requirements for the probability of inadvertent release of martian material into Earth's biosphere and for the probability of contamination of the returned samples with a viable Earth microbe [4, 5]. The Mars Exploration Program has adopted these draft requirements as goals in both the mission studies and the technology program for a future MSR. In the years since these draft requirements were provided, the fields of microbiology and biohazard detection have advanced markedly. The research, technology, and regulations that comprise planetary protection have likewise advanced. The limits of detection and classification of microbial life in environmental samples has improved significantly. In addition, new alternative sterilization techniques for spacecraft and laboratories have been introduced. Progress continues to be made in all of these areas. However, emerging molecular approaches in the search for life have raised concerns about control of organic contamination even after sufficient biological controls are in place. Any forward-looking program of exploration, especially one leading to sample return from Mars, ought to build on experience and existing requirements; anticipate advances in scientific knowledge and associated policies; and support a technology program responsive to both.

After samples are returned to Earth from Mars, planetary protection would require that samples collected on Mars be contained and treated as potentially biologically hazardous until they were shown to meet clearly articulated and approved criteria for release. This has been reaffirmed recently in advice to NASA from the National Research Council [6]. Planetary protection controls would continue until these criteria were met. Thus, technologies associated with sample recovery, transport, and testing would also be part of planetary protection. Although it is often overlooked in discussion of planetary protection for the proposed MSR mission, there would be a continuing need to avoid contamination of samples with Earth life. The rationale is based on the need to avoid false-positive life detection during biohazard assessment in the SRF. These critical elements of planetary protection are described below in the section called Mars Returned Sample Handling.

Notwithstanding an emphasis on MSR-related challenges in the sections that follow, there are significant technology challenges for *in situ* science at any planetary targets of astrobiological interest, including Mars [7]. Biological contamination must never compromise the integrity of life-detection experiments. Thus, measures must be taken to ensure that samples collected by onboard instruments would not experience contamination by the spacecraft itself or other materials brought from Earth. Missions that pave the way for sample return from Mars would require some of the very same technology advances as MSR itself in order to be successful.

6.1 Forward Planetary Protection Technologies

Since the early years of Mars exploration, forward planetary protection technology development has been focused on enabling the preservation of biological and organic conditions for future scientific exploration. The technologies developed over the past decades are adequate for the Mars Exploration Rovers (MER), Phoenix, and MSL type lander missions. However, future Mars exploration during the next couple of decades would likely include a life-detection mission in a region thought to be capable of sustaining life and a MSR mission. Although progress has been made in the last decade to improve and expand implementation options, the current state-of-the-art planetary protection technology portfolio does not have all the necessary elements that would be needed to enable these future missions. The planetary protection requirements for these missions would also challenge us to avoid contamination of *in-situ* and returned samples by Earth microbes and organic compounds.

Overall, there are two distinct approaches that could be taken to meet the more stringent planetary protection requirements associated with life detection and sample return: the system sterilization approach, and the component and subsystem level sterilization approach. The corresponding technologies that would be needed for each approach are identified below (back planetary protection is addressed in a separate section).

System sterilization approach: This approach is similar to "Viking-like" terminal sterilization, i.e., heat treatment of the entire flight system after assembly and before launch. The advantage of the system sterilization approach is its conceptual simplicity. Current planetary protection requirements suggest that if the entire landed system, including instruments, could be sterilized at Dry Heat Microbial Reduction (DHMR) temperature (for the Viking landers, about 112°C for 30 hours), no additional forward (including "round-trip") planetary protection technology other than a system bioshield and the treatment chamber itself would be needed. The technology challenges associated with this approach fall into three main areas.

Hardware compatibility with system sterilization method(s): Further technology investments are needed to eliminate risks of component or subsystem failure due to incompatibility with DHMR treatments. Since the last Decadal Survey, engineering feasibility studies have been conducted based on MER and MSL flight systems to identify subsystems and components at risk from DHMR processing conditions. If a different treatment, such as vapor hydrogen peroxide, to sterilize surfaces were selected, analogous compatibility issues would need to be assessed and resolved.

Terminal sterilization chamber: Design of a sterilization chamber large enough to accommodate an entire spacecraft should be included in the technology program. The feasibility of designing a chamber that could apply more than one sterilization method (such as dry heat and vapor hydrogen peroxide) should be studied.

Biobarrier technology: A full system biobarrier would be required to avoid recontamination of the entire landed system or entire rover following the terminal sterilization process.

Component and subsystem level approach: An alternative approach would be to conduct cleaning and sterilization at the component level followed by a clean-assembly strategy. A strategy of nested subsystem sterilization approaches would need to be used, including aseptic assembly and recontamination prevention, with sensitive subsystems being protected from subsequently applied sterilizing agents. Component level sterilization would have to be accomplished by DHMR or other alternative surface sterilization methods such as hydrogen peroxide or irradiation. For this approach, prelaunch treatments, flight biobarriers, and analytical tools to model contamination risks must be developed. The technology challenges associated with this approach are:

Sterilization method development: All relevant hardware would have to be compatible with approved bioburden reduction methods. If incompatible with heat or vapor hydrogen peroxide, alternative technologies, such as irradiation and precision cleaning to sterility, would need to be developed or adapted *and approved* for planetary protection purposes.

Clean assembly technology to avoid introduction of secondary contamination: Aseptic assembly has been attempted only once in preparation for Mars missions. This was ESA's strategy for the Beagle2 spacecraft. Lessons learned from that experience suggest that effective implementation would be very challenging, and would require at least improvements in existing cleanroom facilities and assembly logistics.

Recontamination prevention: Custom biobarriers to provide shielding would need to be developed [7, 8]. Designs would depend on the function of the subsystems, with different biobarriers being required for protection of key subsystems from recontamination during assembly, at launch, and before in situ operation. (The Phoenix biobarrier was customized for its mission requirements--a single deployment shortly after landing at Mars. While instructive, it would not necessarily fit the needs of other platforms.)

Probabilistic risk assessment (PRA): Unless the system sterilization approach is taken, MSR planetary protection requirements would include a probabilistic limit for round trip viable Earth microbes in the returned sample. This would be primarily to avoid compromise of the biohazard and life detection testing. For *in situ* life detection missions a similar requirement exists to avoid the risk of false positive life detection at Mars. To assess whether a mission scenario would meet the probabilistic requirement, an interactive computer model for sensitivity studies of key parameters would be needed.

Whichever approach would be used for forward planetary protection on future landed missions, there would be a need for molecular inventory technology to enable inventory and archive of biological contaminants on relevant hardware. The need for organic cleanliness increases as the search for life develops ever-increasing emphasis on molecular markers. However, without a practical limit on instrument sensitivities for returned-sample science, cleanliness alone would likely be insufficient. Knowledge of contamination sources would become essential.

The cost of forward planetary protection for a proposed MSR mission has not been established, in large part because it is mission specific. A study performed in 2006 by the Mars Program to assess the hypothetical cost of full system sterilization for MER (post flight, when all components were known) led to an estimate of about $20M for technology development. Estimates for the subsystem cleaning and sterilization approach are provided in Section 12. This estimate is based on assessments of the cost of individual technologies mentioned here as provided by the personnel working on these technologies. Since the forward planetary protection strategy has not been selected at this time, we carry the higher cost in the technology cost estimate shown in Section 12.

6.2 Back Planetary Protection Technologies

Back planetary protection deals with the extremely low probability that Mars material might pose a biological threat to Earth's biosphere. This potential risk leads to a requirement that samples returned from Mars by spacecraft should be contained and tested as though potentially hazardous until proven otherwise. The Mars Exploration Program has adopted a goal proposed by the NASA PPO that the probability of inadvertent release of a single martian particle of size greater than 0.2 microns be less than 10^{-6} [10]. Back planetary protection would require new technologies for three high-level functions:

- Break the chain of contact with Mars
- Preserve containment of the sample
- Assess sample safety

The first part of containment assurance would require "breaking the chain of contact" with Mars, i.e., the exterior of the sample container and the spacecraft that would return it to Earth must not be contaminated with Mars material. Next, the sample container and its seals must survive the worst Earth impact scenario corresponding to the candidate mission profile; the ERV must provide accurate delivery to the Earth entry corridor; and the EEV must withstand the thermal and structural rigors of Earth atmosphere entry—all with an unprecedented degree of reliability. Finally, containment must be maintained after the samples are safely received on Earth. The following paragraphs describe the elements that must be addressed in the technology program in order to meet the overall back planetary protection goal. EEV as a separate technology is described on its own in section 5. The third high-level function of back planetary protection—assesses sample safety—is discussed as part of Mars Returned Sample Handling below.

Breaking-the-Chain & Dust Mitigation: Several scenarios have been identified that would result in Mars material contaminating the outside of the sealed sample container (the "Orbiting Sample" or OS) and/or the EEV. Technology options for mitigation include maintaining the MAV in an Earth-clean state and inserting the sample into an Earth-clean OS on the MAV; ejection of containment layers during ascent and orbit; capturing a dirty OS into a clean container on the ERV and then ejecting the capture device; and use of pyrolyzing surfaces on the OS and/or MAV.

Sealing & Leak Detection: Options for sealing the sample container include brazing, explosive welding, and various types of soft seals, with sealing performed either on the Mars surface or in orbit. Confirmation of sealing could be provided by observation of sealing system parameters and by leak detection after sealing. Wireless data and power transmission might be needed for leak detection.

Containment Vessel (CV): A candidate CV concept that would require development is a flexible liner for the EEV that would be sealed while in Mars orbit. It would be designed to withstand Earth impact conditions (large deformations & piercing ground objects) that would cause a welded metal OS to fail on impact.

Earth Return Targeting: To meet the integrated probability of release goal of one in a million might require unprecedented reliability of navigation to the entry corridor and unprecedented spacecraft reliability while on Earth impact trajectory. Navigation "technology" could include new methods for combining multiple data streams. Spacecraft reliability could be enhanced by improvements in critical components.

Meteoroid Protection & Breach Detection: Protection would be required for both the sample container and the EEV heat shield, with the latter appearing to be the more challenging technology requirement. New lightweight shielding techniques would be needed. Even with these the shield might be excessively heavy leading to an additional requirement for technology to detect a breach of the shield or damage to the EEV.

Systems Engineering & Integration: This element would provide technical integration among the above elements and also with EEV technologies that figure prominently in meeting the overall sample containment goal. Analysis and trade studies would be needed as part of the overall planetary protection technology development effort to identify the most promising combination of technologies. Probabilistic Risk Assessment (PRA) tools would be used to identify and prioritize threats to sample containment and to conduct trades among mitigation options.

6.3 Mars Returned Sample Handling

Mars Returned Sample Handling (MRSH) denotes the "ground segment" of a MSR mission, *i.e.,* the activities occurring after landing of the sample return capsule on Earth. The most recent National Research Council study [6], as well as previous studies referenced therein, included high-level recommendations for MRSH. The NASA PPO sponsored development of a draft protocol [2], which presents one "necessary and sufficient" approach to meeting these recommendations.

After landing, the sample return capsule would be transferred to a Sample Receiving Facility (SRF), where it would be opened and the samples extracted. These samples would initially be studied in one or more SRF(s), as specified by international agreements. The SRF(s) would provide biological containment and capabilities for assessing the possible presence of life and biohazards in representative portions of the samples, as well as preserving the remaining samples for additional research. As continues to be the case for the Apollo lunar samples, the martian rocks and soils would be among the most carefully studied materials in history, not only by biologists but by geologists, geochemists, and atmospheric scientists.

The principles and techniques that would be required for a Mars SRF are generally mature. Biosafety laboratories, the NASA Lunar Sample Facility, pharmaceutical laboratories, and electronic fabrication cleanrooms each contain many of the required elements. However, specific capabilities unique to the MSR mission must be developed, as described below.

Transport of samples: The sample return capsule, containing the samples, would be transported from the landing site to the SRF. In addition, subsequent biohazard and life testing might require transport of sub-samples to additional SRFs, among segments of an SRF, or between an SRF and other specialized laboratories. The transport system would need to meet stringent requirements for safe containment and sample preservation.

Biological safety combined with sample protection: Samples in an SRF would need to be contained in an environment equivalent to a Biosafety Level 4 laboratory. This environment would also have to insure that the samples would be exposed to extremely low levels of organic and inorganic contamination in order to insure reliable results from a wide range of research. While laboratories exist that meet each of these requirements separately, technology to meet the requirements simultaneously must be developed and certified to internationally agreed standards.

Ultra-clean sample manipulation: Samples would initially be subdivided, with portions being tested for biohazards and life, and portions being stored for future detailed analysis. Sample manipulation might be performed by humans, robots, or both. All sample manipulation would be conducted with an extremely high degree of organic and inorganic cleanliness. Capabilities to perform this manipulation using robotic technologies and manual techniques would need to be developed and certified to stringent standards of biosafety and cleanliness.

Sample sterilization: A capability must be developed to render portions of the martian samples biologically sterile. This capability would be required as one segment of overall laboratory safety. Furthermore, the martian samples would also be of intense interest for non-biological studies. If life were discovered in these rocks and soils, sterilization of subsamples could allow such research to proceed outside of biological containment. Sterilization techniques effective against known terrestrial organisms would need to be developed, with an additional degree of safety in recognition of the unknown properties of possible martian life. In addition, the sterilization techniques should preserve—to the greatest extent possible—the isotopic, chemical, and physical characteristics of the rock and soil samples.

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7 Sample Acquisition and Handling

Sample acquisition and handling technology development would be needed to enable future MRR and MSR missions.

Shallow Coring technology would be needed to acquire rock cores that are about 1cm diameter by 5cm long from a wide range of rock types using a rover that might be as small as a MER. Examples of current state-of-the-art technology are the Honeybee Corer Abrader Tool (CAT) which provides rotary friction based coring [1], the Mini-corer developed for the '03/ '05 MSR mission which was later cancelled [1], the Alliance Spacesystems Low-Force Sample Acquisition System (LSAS) coring tool which provides rotary percussion coring [2], and the MSL mission Powder Acquisition Drill System (PADS), which acquires rock powder samples with a rotary percussion tool but would not provide the functionality required for the candidate MRR mission. The CAT and Mini-Corer were specifically developed for a flight mission, but were not actually flown. LSAS is a technology development tool that was not developed for a specific flight mission. Rotary percussion-based coring requires significantly lower weight on bit compared to rotary friction based coring. This could better allow for an arm-based coring system compared to a more constrained body-mount system architecture. While specific tool functions have been demonstrated in prototype tools, no tool provides an integrated set of functions satisfying all mission needs. A significant effort would be needed to develop and validate a coring tool with required overall functionality and low enough mass to be feasible for core acquisition from a low-mass rover in challenging, e.g. sloped, terrain. Since soil samples would also need to be acquired, it would be beneficial—though not a requirement—for the coring tool to acquire these samples as well.

Sample Transfer, Sealing, and Caching technology would be needed to transfer samples from the coring tool into individual sample tubes in the handling system on the rover, seal the tubes, and store the tubes in a canister on the rover. Depending on the architecture of the MRR/MSR mission concepts, the canister containing core samples would be transferred to the future fetch rover to transport the samples to the lander having a MAV (a three-launch MSR architecture concept), or the canister would be transported to the MSR lander by the caching rover (a two-launch MSR architecture concept). The Bottom Loading Caching (BLoC) subsystem concept represents one architectural solution [3]. A significant effort would be needed to develop and validate a system that is robust to the wide variety of rock types and that could also handle cores that might have broken during acquisition, as well as satisfy stringent planetary protection and contamination control requirements.

Sample Processing technology might be needed to subsample and distribute samples to *in-situ* instruments for the MRR mission. The Honeybee Mechanized Sample Handler (MeSH) [1] and rock crusher developed for MSL, but subsequently not used, represent current technology for this function. The need to process unknown sample material makes development of a robust processing system particularly difficult.

System Implications of sample acquisition and handling for planetary applications is challenging due to the unknown properties of the potential samples, limited spacecraft resources, and the need to satisfy stringent planetary protection and contamination control constraints (Planetary Protection Section 6.). There are numerous distinct functions in the sample acquisition and handling system that would need to be designed to work together in one robust system. Technologies for the various functions of the system would need to be developed, the subsystems comprising the technologies would need to be developed and validated and the overall system would need to be integrated and validated in a relevant environment. A multi-year program would be needed to develop and validate the component technologies and integrated system.

References:

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8 Mars Ascent Vehicle

The MAV would be a critical component of any MSR mission concept. The baseline MAV design would require some technology development in addition to extensive testing and analysis to meet the mission requirements. The baseline system might also pose a mass challenge for the existing architecture. Alternative technologies exist with potential to reduce the MAV mass, but additional technology development and testing would be required. The MAV is, in principle, a small launch vehicle that would require technology development, system development and integration, qualification, and testing that must be initiated several years prior to the MSR PDR.

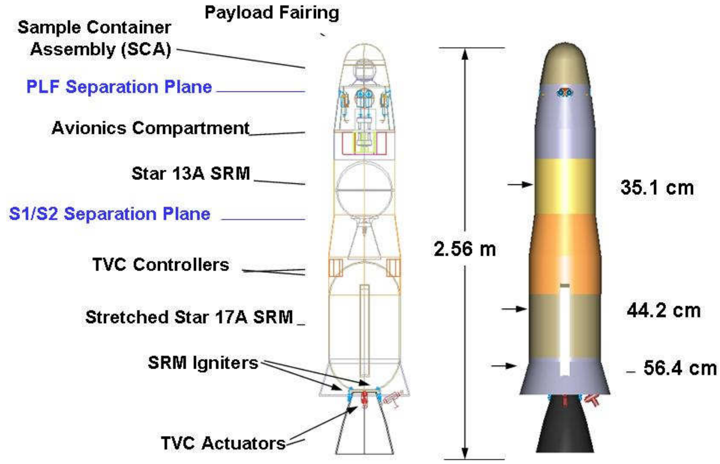

Figure 1. Baseline Two-stage Solid MAV Concept. [1]

Capability Description and Needs: While the architecture of the MSR mission concept and subsystem level trades are still under evaluation, the MAV would have fundamental requirements to accommodate and deliver a 5 kg Orbiting Sample (OS) with a 16 cm diameter to an orbit suitable for rendezvous with and capture by the ERV. This OS is designed to contain 0.5 kg of martian samples. These requirements would specifically include:

- Delivery to 500 +/- 100 km orbit
- Inclination accuracy to +/- 0.2°
- Ability to launch from +/- 30° latitudes
- Storage capability up to one Earth year on Mars surface
- Continuous telemetry during operation

The baseline architecture of the MSR mission concept and MAV would include a transit phase from Earth-to-Mars, an EDL phase that assumes the use of the MSL-based Skycrane, long-duration storage in a thermal isolation "igloo," erection, and launch. Each phase of the mission would have its own unique requirements including environmental control, high lateral g-loads, planetary protection, thermal cycling, and long-term storage [2].

The baseline MAV design, shown in figure 1, is a three-axis controlled two-stage solid system based on a Lockheed Martin design. The primary propulsion system is based on two ATK Star heritage motors. The baseline system would include a hydrazine-based attitude control system (ACS) and use thrust vector control (TVC) with the solid motors.

The state-of-the-art, solid-based propulsion system MAV is estimated to have a total landed mass of approximately 285 kg and would require thermal maintenance. ATK Star motors have significant flight heritage, but the following potential changes must be addressed:

- The motor must be stretched to increase the amount of solid fuel required (routine practice by ATK)
- A new composite overwrap case might be preferred and must be assessed to same mass
- A low-erosion throat might improve system performance (i.e., specific impulse or ISP)
- The Thrust Vector Control system is not qualified for martian environment environments and must be qualified for cold temperature
- Propellant grain design would require analysis and testing for both the high lateral g-loads and long-term storage.
- It might be required to keep the flight proven propellant formulations above 230 Kelvin with ability to raise the temperature higher just prior to launch for added performance.

The MAV is a critical part of the MSR mission concept. It is not enough to develop and test individual subsystems or components. It is also the one part of the mission whose reliability might be most questionable in the Mars surface environment. System-level tests would be essential prior to MSR PDR to ensure mission feasibility.

Alternative Technologies: There are several alternative technologies for the MAV still under consideration. Initial analysis estimates mass savings of 20% would be achievable. Alternative technologies are primarily for liquid-based propulsion systems that would have higher propellant performance. Military technologies have the potential to be adapted for MAV application. Also, previous MTP investments on small pump technologies have MAV applicability--a leak-tight, reliable propellant pump would lead to small, high-performance propulsion stages. These alternative technologies would require technology development and extensive testing for the martian environment.

Development Plan: The development approach is currently to better characterize the system reliability and expected performance of alternative propulsion systems while developing the baseline solid propulsion system. To reduce risk, a MAV unit would need to be developed and flight tested in a relevant environment (testing both landing conditions, i.e., g-loads, and Mars environment) by the MSR lander PDR timeframe, which would be 4–5 years prior to launch. Therefore, the propulsion system elements must be at TRL 6 and ready for integration into a flight test unit 7–8 years prior to launch.

References:

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9 Rendezvous and Sample Capture

Rendezvous and sample capture would be a complex series of distinct operations involving hardware and software and individual actions that might extend over a period of up to a month during the capture phase of the MSR mission concept. Various conceptual operational scenarios are being considered. One concept has the recovery ship in orbit around Mars when the OS would be launched from the martian surface. In this scenario, the MAV would be launched when the recovery orbiter is overhead and maintain a direct link with the orbiter until mating with the OS. An alternate operational concept is that the OS would be launched into low Mars orbit and the orbiter would arrive months or perhaps years later. In both cases, the following series of operations in the following sequence would be required: Rehearsals, where some or all of the rendezvous and capture process would be accomplished on Earth or Mars orbit prior to the need for MSR; Search and Detection, where an orbiting OS of partially or wholly unknown orbit is located; Tracking and Approach, where the located OS would be followed and orbit of the capturing vehicle adjusted to match; and Capture and Sample Transfer, where the OS would be physically captured and moved to the EEV.

A number of missions have demonstrated technologies that could be adapted to use on MSR. These include the navigation imaging systems of Mars Reconnaissance Orbiter (MRO) and Orbital Express (OE) [1]; the LIDAR systems of XSS-11 and OE; the onboard navigation systems of Deep Space 1, Deep Impact and OE; the rendezvous systems of the Shuttle, the next generation version to fly on Orion, and that of XSS-11. The Mars and other NASA technology programs have also made advances in capture mechanisms, LIDARs, software architecture and other areas that could be applied [2]. Nevertheless, in order to accomplish the above functions needed for an MSR mission, a range of technologies must be developed to maturity or certain elements must be adapted and matured to TRL 6 by mission PDR:

- **Autonomously actuated mechanisms for orbiting sample capture**: The devices which contact, restrain and ingest the OS could be of several different architectures, some of which have been tested, but all of which would need further development and testing to be at sufficiently high TRL to fly on MSR. Technology challenges would include control and containment of initial impact momentum, lightweight structures, physical contact sensors and reliability.

- **Optical sensors**: For mid- and near-field imaging, some further development of passive optical sensors, and possibly IR sensors, would be necessary to meet the size, mass and reliability requirements of MSR. Imager technology enhancement would include long-life and low-noise optical detectors and robust and lightweight gimbaling for proximity operations. Long-range searching and detection (up to 10,000km range) and LIDAR have been addressed by the MTP and industry, and neither needs further work.

- **OS Radio Beacon**: The OS would very likely be equipped with a radio beacon, most likely battery powered. The required capability and complexity of this beacon would need to be studied and traded against the functional enhancements provided to the capture process. Such benefits would range from a moderate enhancement in detection ability to a fully parallel rendezvous-sensor capability. Technology challenges would include single micro-integration of coherency, ranging signals, and programmability. Extreme-lightweight power supply would be a substantial challenge, while maintaining the high uniform albedo of the external shell of the OS. Extensive work has been performed on the receiving side of the beacon radio link, with the Electra software radio concept, and this would require little further technology development.

- **Autonomous Rendezvous GN&C and Command and Control System**: Though the OE, Deep Space 1, Deep Impact, and soon the Constellation Program Orion mission, have developed GN&C systems capable of autonomous rendezvous. The particular application of these to the MSR mission scenario would require adaptation, especially in the design of the autonomous sensing and reaction to the events of the rendezvous [3, 4]. The technology challenge would be principally this "intelligence" aspect of the rendezvous, including assuring spacecraft and sample safety and general fault responses. The missions mentioned above have developed very substantial navigation algorithmic capability that would be leveraged.

- **Technology Validation Tests**: A test of rendezvous and capture in an environment that well mimics the challenges of doing so on Mars orbit would be required—if not actually done at Mars on another or precursor mission [5]. There is a range of possible approaches to this test from an actual on-Mars-orbit rehearsal with a dummy OS to extensions of the KC-135 micro-g environment tests already accomplished by the MTP [6]. Technology challenges would include utilization of an integrated system of sensors; capture mechanisms and software.

References:

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10 Rover Technology

This section describes the rover and avionics technologies that are anticipated to meet the needs and challenges of the candidate MRR mission and the 2020+ fetch rover of the MSR mission concept, both of which are under study.

The sample caching rover mission would be designed to deliver a solar-powered rover to the martian surface. The landing error ellipse is projected to be smaller than MSL's, as indicated in the EDL section, i.e., ~7 km radius in the semi-major axis. The rover mass is expected to be less that MSL's Curiosity and heavier than MER. The baseline sampling requirement would be to collect 20 samples at four sites outside the landing ellipse within one Earth year [1]. At each of the four sites (sites are planned to be at least 500 m apart), the rover would collect five samples that could be up to 50 m apart. The rover would then drive to a safe location to deposit the 20-sample cache for the 2020+ fetch rover to retrieve. For such a scenario, the total traverse distance for the sample-caching rover would be ~10 km. Assuming that 10 sols would be required by the scientists to select each sampling region and each sampling operation (which include approach, analyze, prepare, core, cache and seal the sample) would take 5 sols, a total of 215 sols would remain for traversing. Assuming 30% loss of sols due to unexpected environmental and terrain conditions or system anomalies, the rover would be expected to traverse 10 km in 150 sols, i.e., ~67 m/sol on average.

If hazard avoidance technology, discussed in the EDL section, is implemented, there is a potential that the rover could be landed in a terrain within which science targets would be closer and a go-to traverse might not be required. Therefore, the 67 m/sol stated above might be relaxed.

The 2020+ sample retrieval mission would be expected to land a MAV together with a solar-powered fetch rover that would retrieve the sample canister. The lander would land as close as possible to the sample canister using precision landing technology (see Section 4). Assuming a landing ellipse accuracy of 6 km in the semi-major axis, the 100 kg fetch rover would be able to complete its round trip traverse of 12 km to retrieve the sample cache and deliver it to the MAV. The fetch rover would use 150 sols for its round-trip traverse. The remainder of the time would be allocated for sample retrieval and deposit as well as contingency time for immobility during dust storms. Thus, the traverse requirement for the fetch rover would be on the order of 80 m/sol using a rover of a half to a third the mass of the sample caching rover.

The state-of-the-art MER/MSL rovers are capable of a mechanical traverse speed of up to 252 m/sol (assuming 2 hours of traverse per sol) without sensing the terrain for hazards. This mode of operation is very risky and cannot be baselined for a future mission. Risk can be reduced by using on-board autonomy to detect and drive around obstacles and sense high-slip hazardous conditions. Using on-board autonomy, the MER rover traverse speed drops to less than 29 m/sol in terrains with relatively few obstacles. Traverse distances per sol depend highly on terrain conditions and available power. Based on above considerations, the current rover speeds would not satisfy the required traverse distances without advances to both computing avionics and autonomy algorithms.

To meet the traverse requirement of 67 m/sol for the sample caching rover and 80 m/sol for the fetch rover in moderately challenging terrain, advances in avionics and rover autonomy would be needed.

Rover Autonomy

To meet the traverse distance requirement while ensuring rover safety on moderately challenging terrains, we would need to: (1) keep rover autonomy algorithms always enabled; (2) advance autonomy to handle moderately challenging terrains; and (3) increase the autonomy throughput at least three fold as compared to state-of-the-art rovers. In addition to enhancing traverse autonomy, advances to reduce the operational cycles for approaching and collecting measurements from multiple candidate targets are expected to reduce the number of sols needed to select and gather the 20 core samples.

The autonomy cycle for the MER rovers, which is similar to the planned cycle for MSL, constitutes of a sense, think, and drive cycle. Each cycle, which typically covers a half-meter step, takes as long as three to four minutes for sensing, assessing the traversability of the terrain, completing the traverse step, and measuring the resultant slippage. The energy usage for autonomous drive represents a five-fold increase relative to a blind drive, primarily because of the sensing and computational requirements. Advances in rover autonomy would include an increase in sensing and computation throughput through the parallelization of computation. Additionally, it would include algorithmic advances to reduce the amount of computation while increasing robustness. A further advancement to the traverse speed would include the parallelization of the sequential process to enable "thinking while driving," and the adaptation for the amount of computation based on terrain difficulty. By combining improved rover traverses with an ability to safely deploy instruments on targets that are designated from a distance, surface operations would require fewer sols to achieve mission requirements.

Rover Avionics

The current expectation is that MSL rover avionics and motion control would not meet the throughput needs for potential sample caching and fetch rovers. Also, the form factor and excessive mass could not be accommodated on the 100 kg fetch rover. Additionally, the imaging avionics (cameras and their interface to the main processor) used on both MER and MSL would need increased bandwidth and processing to operate while a rover is driving.

In addition to the above, an increase in the overall efficiency of power generation from the solar arrays would be necessary. State-of-the-art solar cells used on the MER rovers were not optimized for the light spectrum on the surface of Mars. By designing such arrays for that spectrum and through improvements in solar cell technology, an improvement of 33-35% in efficiency could be achieved by 2015.

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11 Science Instruments

Trace Gas Orbiter Mission Concept

TGO's suggested payload would include the following instruments: Solar occultation Fourier transform infrared (FTIR) spectrometer, Sub-millimeter spectrometer, Wide-angle camera, Thermal-IR spectrometer, 1 to 2 meter per pixel class imager. All of these instruments were considered ready for the 2013 MSO opportunity, so any technology development for these instruments would be enhancing rather than required [1].

Network Mission Concept

The Network mission payload would be a combination of geophysics and atmospheric sensors: Geophysics: Seismometers, heat flow, electromagnetic Sounding; Atmospheric: pressure, temperature, wind, water vapor, upward sounding, and atmospheric trace gas composition. Potential areas needing technology development include engineering of the instruments to survive hard landings (for some mission concepts). Examples of most of these instruments have been engineered and tested for flight with the exception of the heat flow probes (deployment is the issue) and atmospheric trace gas composition (the current version, MSL SAM, is too large for the Network mission). The key instruments requiring development would be the heat flow probes and the atmospheric trace gas measurements [2].

MRR Mission Concept

The payload concept for MRR would include the following [3]:

<u>On the arm</u>:

Micro-imaging, mineralogy, organic detection, elemental analysis, micro-elemental analysis

On the mast:

Imaging and remote mineralogy

Other candidates: ground penetrating radar, remote geochemistry, magnetometer, meteorology package, atmospheric composition/isotopes

Most of these have been demonstrated on MER or developed for MSL. The ones still needing development are organic detection and ground penetrating radar.

MSR Mission Concept

For the three-launch architecture concept, no new science instruments would be required.

References:

[1] Mike Smith, MSO SDT Update, presentation at MEPAG #20, March 2009. http://mepag.jpl.nasa.gov/meeting/mar-09/index.html

[2] W.B. Banerdt, personal communication

[3] MEPAG MRR-SAG-1 (2009). Report from the Mid-Range Rover Science Analysis Group, XX pp., posted July XX, 2009 by the Mars Exploration Program Analysis Group (MEPAG) at http://mepag.jpl.nasa.gov/reports/

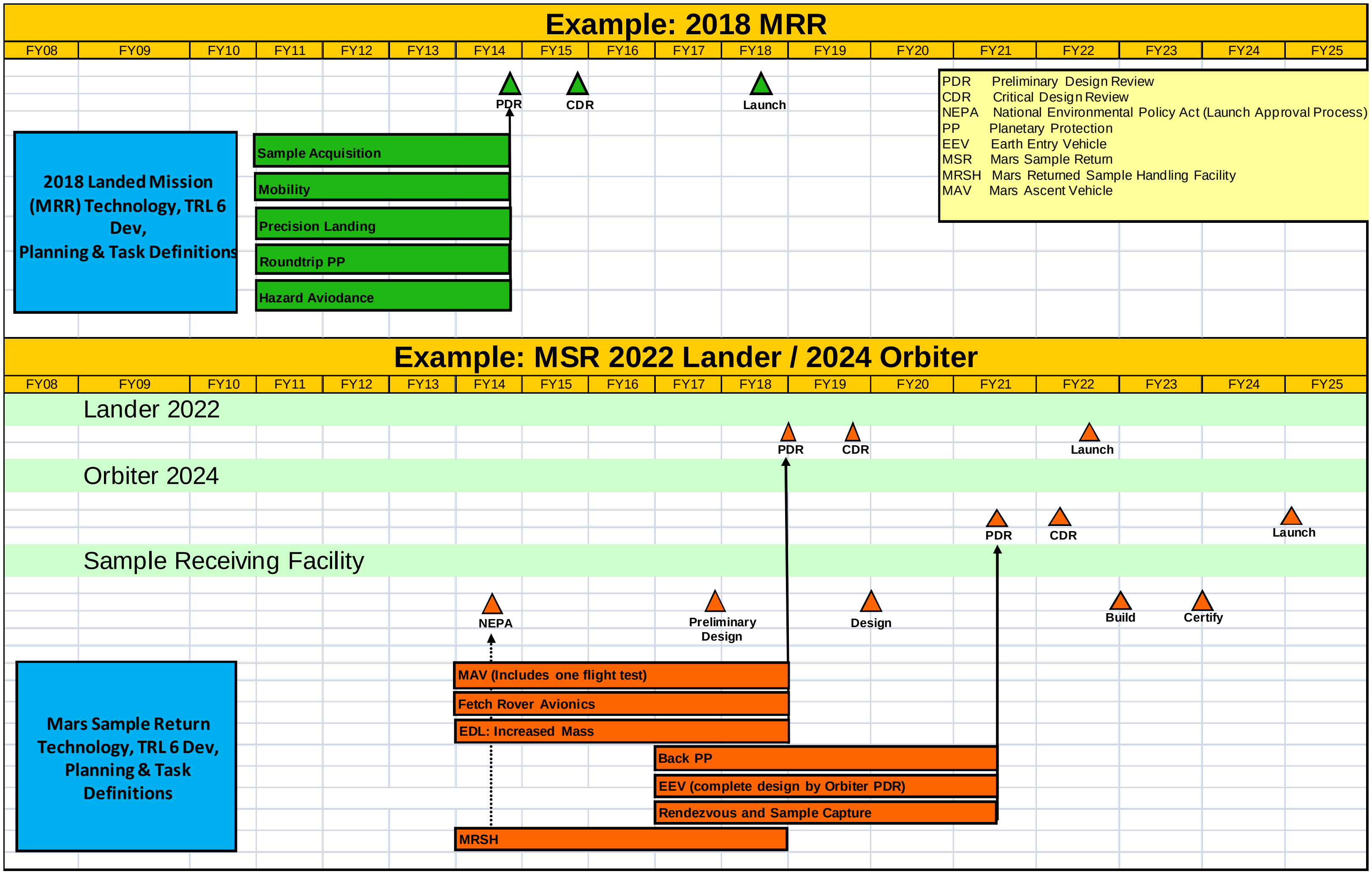
12 Cost and Schedule

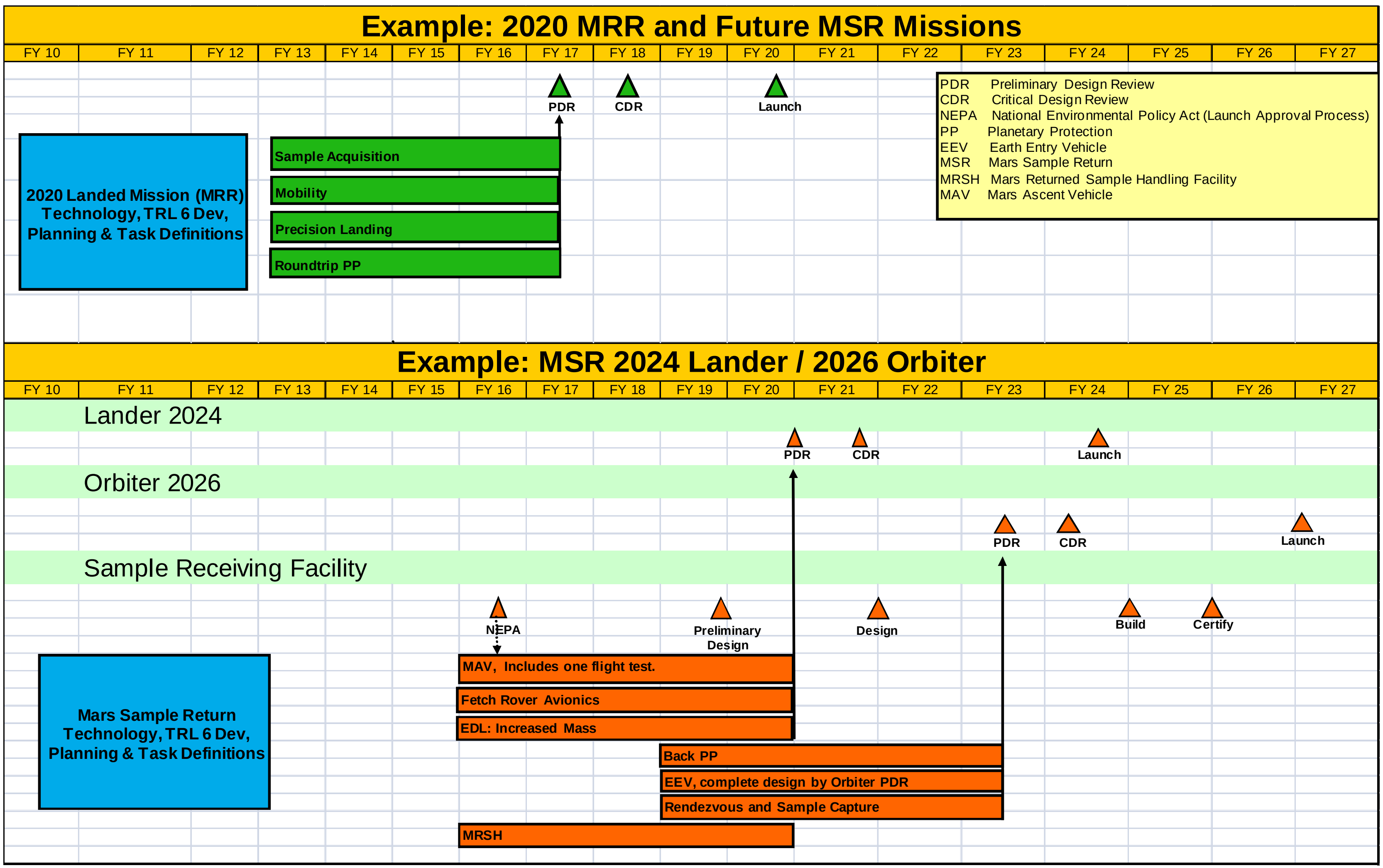
As was indicated in Section 3, cost estimates for various technology development elements were developed in several stages, updating the information by consulting the domain experts within the community. Numbers for the proposed MAV are based on industry studies in the past and include recent updates. The table below provides a summary for various technology developments discussed in this document, except for science instruments which are funded through MIDP on an on-going basis.

Technology Cost for MRR Mission Concept			
Reference	**Technology**	**Cost (FY '09 M$)**	**Mission**
Section 4	EDL-Precision Landing	3	MRR
Section 4	EDL-Hazard Detection and Avoidance	16	MRR
Section 6.1	Forward PP	33	MRR
Section 7	Sample Acquisition	27	MRR
Section 10	Rover Technology - Rover Autonomy, Distributed Motor Control	18	MRR
Total	**MMR Technology**	**97**	**MRR**

MSR Concept, Assuming MMR Cache is Available			
Reference	**Technology**	**Cost (FY '09 M$)**	**Mission**
Section 4	EDL- Lander Mass incresaed up to 10%	10	MSR-Lander
Section 5	EEV	42	MSR-Orbiter
Section 6.2	Back PP	48	Architecure dependant: 100% MSR-Orbiter or 50/50 split between MSR Lander and Orbiter
Section 6.3	MRSH	24	MSR Orbiter
Section 8	MAV Technology	19	MSR Lander
Section 8	MAV Flight Test	118	MSR Lander
Section 9	Rendezvous and Sample Caprure	20	MSR Orbiter
Section 10	Rover Technology - Rover Avionics	22	MSR-Lander
Total	**MSR Technology**	**303**	**MSR**

The following figures show a typical schedule for MRR 2018-2020 and MSR 2022-2024 project concepts


Example: 2018 MRR
FY08 FY09 FY10 FY11 FY12 FY13 FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25
PDR
CDR
Launch
PDR Preliminary Design Review
CDR Critical Design Review
NEPA National Environmental Policy Act (Launch Approval Process)
PP Planetary Protection
EEV Earth Entry Vehicle
MSR Mars Sample Return
MRSH Mars Returned Sample Handling Facility
MAV Mars Ascent Vehicle
2018 Landed Mission (MRR) Technology, TRL 6 Dev, Planning & Task Definitions
Sample Acquisition
Mobility
Precision Landing
Roundtrip PP
Hazard Aviodance
Example: MSR 2022 Lander / 2024 Orbiter
FY08 FY09 FY10 FY11 FY12 FY13 FY14 FY15 FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25
Lander 2022
PDR
CDR
Launch
Orbiter 2024
PDR
CDR
Launch
Sample Receiving Facility
NEPA
Preliminary Design
Design
Build
Certify
Mars Sample Return Technology, TRL 6 Dev, Planning & Task Definitions
MAV (Includes one flight test)
Fetch Rover Avionics
EDL: Increased Mass
Back PP
EEV (complete design by Orbiter PDR)
Rendezvous and Sample Capture
MRSH


Example: 2020 MRR and Future MSR Missions
FY 10
FY 11
FY 12
FY 13
FY 14
FY 15
FY 16
FY 17
FY 18
FY 19
FY 20
FY 21
FY 22
FY 23
FY 24
FY 25
FY 26
FY 27
PDR
CDR
Launch
PDR Preliminary Design Review
CDR Critical Design Review
NEPA National Environmental Policy Act (Launch Approval Process)
PP Planetary Protection
EEV Earth Entry Vehicle
MSR Mars Sample Return
MRSH Mars Returned Sample Handling Facility
MAV Mars Ascent Vehicle
2020 Landed Mission (MRR) Technology, TRL 6 Dev, Planning & Task Definitions
Sample Acquisition
Mobility
Precision Landing
Roundtrip PP
Example: MSR 2024 Lander / 2026 Orbiter
FY 10
FY 11
FY 12
FY 13
FY 14
FY 15
FY 16
FY 17
FY 18
FY 19
FY 20
FY 21
FY 22
FY 23
FY 24
FY 25
FY 26
FY 27
Lander 2024
PDR
CDR
Launch
Orbiter 2026
PDR
CDR
Launch
Sample Receiving Facility
NEPA
Preliminary Design
Design
Build
Certify
Mars Sample Return Technology, TRL 6 Dev, Planning & Task Definitions
MAV, Includes one flight test.
Fetch Rover Avionics
EDL: Increased Mass
Back PP
EEV, complete design by Orbiter PDR
Rendezvous and Sample Capture
MRSH